Impact of refined HVAC systems efficiency determination on EPR energy calculations

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1. ABSTRACT

In this paper, integrated yearly dynamic simulations of a thermal system coupled to 6 variants of a medium-sized office building are performed and discussed. A traditional hydronic heating system is considered, consisting of a modulating condensing gas boiler and radiators in every heated zone. No active cooling is provided, though only building variants able to provide summer comfort through passive cooling only are selected. Hygienic ventilation is provided by a mechanical extraction system.

From the integrated simulations, monthly efficiencies for the generation, distribution and emission subsystems are deduced. The latter are expressed depending on the monthly heat-balance ratio, which equals the ratio of heat gains over heat losses on the building level. The heat-balance ratio thus represents the part load ratio, but can be calculated without taking the system into account. This variable is used in order to generalize the results and at the same time use them in an Energy Performance Regulation (EPR) context, which requires relatively simple calculations where the system cannot be taken into account in detail.

The resulting subsystem curves correlate quite well with the monthly heat-balance ratio (R^2-values of 0.84 or higher). These curves show the heating subsystem efficiency drops in months with higher heat-balance ratios (and thus lower heating demands). These refined efficiencies are subsequently used in an EPR-type calculation, in which the monthly net heating demand is divided by the subsystem efficiencies to estimate the monthly final energy use. The results of this calculation are compared to similar calculations using annually averaged efficiencies deduced from the integrated simulations and using the default fixed EPR values for the subsystem efficiencies. It is shown that using the refined efficiencies yields better results in intermediate months, when the heating demand is lower. However, when looking at the total annual final energy use, the impact of using the refined efficiencies is modest.

Keywords: Integrated simulation, HVAC system analysis, efficiency, building energy use

2. INTRODUCTION

In the current context of global efforts towards a less energy-intensive society, accurately estimating the energy use of building designs becomes increasingly pertinent. In the framework of the European Energy Performance of Buildings Directive (EPBD), a series of standards was developed, of which the most elaborate is EN13790 (ISO/FDIS, 2007), offering procedures to estimate the characteristic total final energy use of buildings. All are based on the same principle of dividing the net energy demand, quite straightforward to calculate, by the efficiencies of the subsystems, i.e. emission, distribution, generation, storage and control. The current Energy Performance Regulations (EPR) calculation procedure of Flanders, the northern part of Belgium (Flemish Government, 2005), contains standard tabulated values for those subsystem efficiencies, constant throughout the year. More refined approaches exist, taking several influences into account, for example in EN15316 (CEN, 2007b). However, all methods to calculate the subsystem efficiencies are defined at that very subsystem level, ignoring the complex interaction of the building, the occupants and the system. As argued by Zhang et al. (2006) and Van Der Veken and Hens (2008), an integrated approach is therefore better suited, where a dynamic simulation is set up that includes both the building and the system (denoted as level D calculations in EN15316). Though holistic studies on HVAC system performance characterisation are rather rare (Shahrestani et al., 2013), this approach has been successfully adopted in a few studies, illustrating the influence of the building and the building use on the HVAC system efficiency.

Korolija et al. (2011) compared the energy use of a very well insulated office building equipped with either an all-air VAV system or fan coil units combined with a dedicated outdoor air system. The system efficiency was assessed for different levels of internal heat gains. Its value for the same secondary HVAC system was found to vary for different building loads, though no formal correlation is deduced. An analogue observation was made in ref. (Korolija et al., 2009), where the energy use of an office building with different secondary HVAC systems, namely CAV and VAV, was compared. The system efficiency varies not only with different control settings, but also with the insulation level of the building.

The CAV, VAV and fan coil systems plus the combination of chilled ceilings and radiator heating were further analyzed by Korolija (2011). A large amount of office buildings varying in orientation, insulation, glazing-to-wall ratio, glazing type, structural shading and daylighting coupled to the 4 secondary systems were simulated for several weather data files using an integrated approach. The results indicated clearly that the annual heating and cooling system efficiency and the annual auxiliary energy use for the different systems are not constant, but depend instead on the building variations.

Peeters et al. (2008) performed an analysis of residential heating energy use for several combinations of boiler type, boiler control and emitter control through integrated dynamic simulation of building and systems. A rather strong relationship between the monthly total efficiency and the heat-balance ratio of the building, the ratio of heat gains over heat losses, was found. This effect was attributed to component efficiencies decreasing for lower part load ratios and overheating due to imperfect control occurring mainly when heating demand is low.

Bauer (1999) established correlations between the heating emission and control efficiency and a parameter characterising the building for different combinations of emitter and control systems. His findings are integrated in the German standard DIN 4701-10 (DIN, 2003).

In this paper, the integrated approach is used to assess the performance of a relatively simple heating system commonly found in office buildings in Flanders, including their auxiliary energy use. In extension to the research carried out by Korolija et al. (2013), both the primary and secondary HVAC system are modelled. Radiator heating, coupled to a condensing gas boiler is considered. The aim of this paper is to analyze the monthly subsystem efficiencies calculated with this integrated approach and to express them depending on the monthly building's heat-balance ratio, in analogy with the work of Peeters et al. (2008) for residential buildings, to acknowledge the influence of the building and building use on the HVAC system performance. These newly defined subsystem efficiencies will subsequently be compared to the current standard EPR values and their influence on the EPR calculation of characteristic energy use assessed.

3. TERMINOLOGY

The conceptual framework for the evaluation of heating systems in buildings as laid out in the European standard EN 15316 (CEN, 2007b), serves as the basis for this study, both for heating and cooling system analysis. The performance of the system is analyzed at four sublevels:

emission, distribution, storage and generation. The generation and storage together form the primary HVAC system, while the emission and distribution form the secondary HVAC system. Figure 1 offers a graphical overview of this framework.

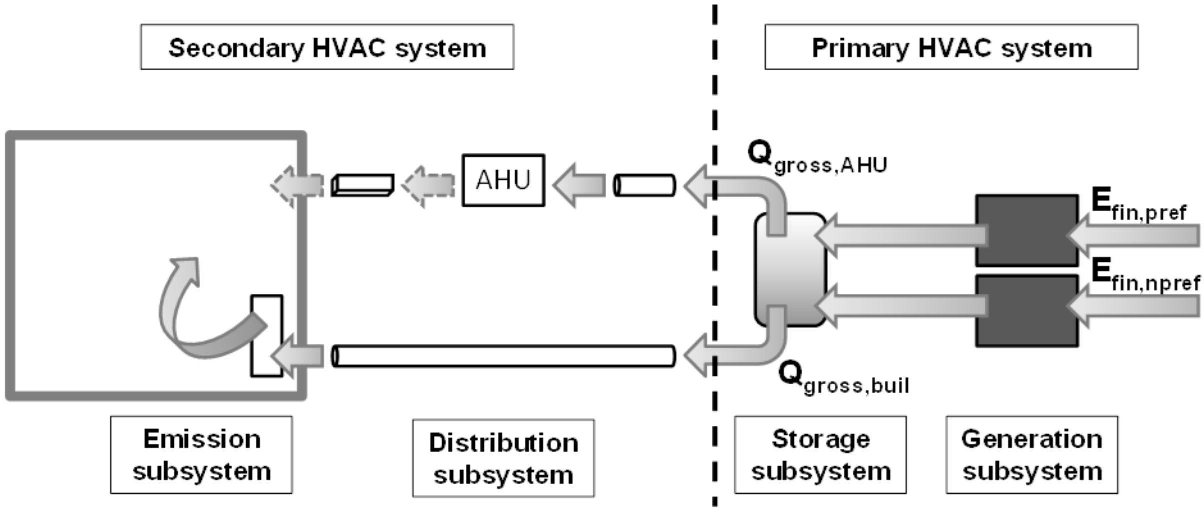


Figure 1: Conceptual scheme of subsystems and energy flows in an HVAC system (air thermal flows are indicated by dotted arrows, all other thermal flows are hydronic).

Emission and distribution are divided into building zone level, denoted with index buil, and air handling unit level, denoted with index AHU, in analogy with the German standard DIN V 4701-10 (DIN, 2003). The distribution on air handling unit level is partly hydronic (between the primary HVAC system and the AHU) and partly by air transport (between the AHU and the building zone).

The control of heat and cold emission in the zones is not regarded as a separate sublevel, as is sometimes done, but instead integrated in the emission efficiency (η_{em}), by defining the latter as the ratio between the net energy demand and the energy delivered to the emission device. In addition to imperfect control, emission efficiency losses can occur due to temperature stratification, shielding of the emission device or through ‘short-circuiting’ by locally heating the building envelope, increasing the heat losses (or vice versa for cooling).

Distribution efficiency (η_{dis}) losses are due entirely to energy losses - in case of heating - or gains - in case of cooling - through the walls of the hydronic pipes and air ducts to unconditioned spaces. The thermal insulation of the pipes and ducts obviously plays a key role, but also the temperature difference between the fluid and the environment and the total length of the distribution network. In addition, strongly intermittent operation of the system will lower the distribution efficiency, since the fluid content will cool down in between heating periods (or vice versa for cooling).

The storage efficiency (η_{stor}) is, quite straightforwardly, equal to the ratio of net energy output to the distribution subsystem over the energy input from the generation subsystem. Energy transfer through the wall of the storage tank is the only source of efficiency loss. Energy storage is however not included in the HVAC system typologies considered here (see 4.2).

The generation efficiency (η_{gen}) equals the ratio between the thermal energy output of the generation subsystem and the energy input by the respective energy carrier, limited to electricity or natural gas in this research. The source of efficiency losses depends highly on the type of generation device.

The definitions and symbols of the main quantities discussed in this section are summarized in Table 1.

Table 1: List of symbols and definitions of the terms used to describe HVAC system performance.

Term	Symbol	Definition
Net energy demand	Q_{net}	The energy that needs to be delivered in a building zone during a certain time to maintain the desired temperature.
Gross energy demand	Q_{gross}	The energy that needs to be delivered during a certain time to the secondary HVAC system.
Final energy use	E_{fin}	The energy used during a certain time by the generation systems.
Auxiliary energy use	W_{aux}	The energy used during a certain time by those components of the HVAC system that do not generate heat or cold (pumps, fans, humidifier, ...)
Primary energy use	E_p	The energy use converted to energy source level; default conversion factors (f_p) of 1 for fossil fuels and 2.5 for electricity are used (Flemish Government, 2005).
Emission efficiency	η_{em}	The ratio between the net energy demand and the energy delivered to the emission subsystem.
Distribution efficiency	η_{dis}	The ratio between the energy delivered to the emission subsystem and the energy delivered to the distribution subsystem.
System efficiency	η_{sys}	The ratio between the net energy demand and the gross energy demand.
Storage efficiency	η_{stor}	The ratio between the energy delivered to the distribution subsystem and the energy delivered to the storage subsystem by the generation subsystem.
Generation efficiency	η_{gen}	The ratio between the final energy use and the energy delivered to the storage subsystem (or directly to the distribution subsystem, if no storage tank is placed) by the generation subsystem.
Total efficiency	η_{tot}	The ratio between the net energy demand and the primary energy use.

4. METHODOLOGY

4.1 General

The analyses of the subsystem efficiencies are carried out on a monthly time base, which is also used in the context of the EPR. In order to generate enough data points for the analysis, the HVAC system is sized for and implemented in several building design variants of a reference office building (section 4.2). A detailed discussion of the selected HVAC system is given in section 4.3.

Integrated dynamic simulation models are set up for every combination of building design variant and HVAC system (section 4.4). Apart from the integrated simulation, a building simulation to calculate the net energy demand needs to be performed. The time step of the latter is typically 1 hour.

In order to be able to compare the performance of the different systems fairly, the resulting thermal comfort in the building needs to be similar in all cases. The thermal comfort is evaluated according to the degree hours criterion of the European standard EN15251 (CEN, 2007a), with the difference between the occurring temperature and the limit temperature as weighting factor. Deviations during 5% of the occupied time on a yearly and monthly basis are accepted, which means about 100 h per year and about 10 h per month. In addition to thermal comfort, the indoor air quality (IAQ) in terms of amount of fresh air per person is equalized for all considered systems. An air flow rate of 36 m3/h per person for the design occupancy (IDA2 class, (CEN, 2004)) is supplied in each case.

The monthly subsystem efficiencies will be expressed as a function of the monthly heat-balance ratio of the building γ, as defined in EN13790 (ISO/FDIS, 2007). This variable represents the part load ratio (Olesen, 2001), but can be calculated without knowledge of the HVAC system nominal properties. In the framework of the EPR, this is a prerequisite. It incorporates the climate, building characteristics, internal gains and occupant behaviour. Equation 1 defines the heat-balance ratio depending on the building's solar heat gains (Q_{sol}), internal heat gains (Q_{int}), transmission heat losses (Q_{tr}), ventilation heat losses (Q_{vent}) and infiltration heat losses (Q_{inf}). The heat-balance ratio is closely related to the net energy demand. As shown in ref. (Van Der Veken & Hens, 2008), it has a strong correlation with the overall heating system efficiency in dwellings.

$$\gamma = \frac{Q_{gains}}{Q_{losses}} = \frac{Q_{sol} + Q_{int}}{Q_{tr} + Q_{vent} + Q_{inf}} \quad [-] \tag{1}$$

As mentioned before, the current EPR calculation of the characteristic primary energy use consists of two steps, identical for cooling and heating energy use. The net energy demand for each month ($Q_{net,m}$) is calculated in a first step, which is then divided by the subsystem efficiencies (and primary energy conversion factor) to obtain the primary energy use. Currently, those subsystem efficiencies are constant throughout the year.

$$E_p = \sum_{m=1}^{12} \frac{Q_{net,m}}{\eta_{sys}\eta_{gen}f_p} \tag{2}$$

The refined approach studied in this paper consists of defining monthly subsystem efficiencies depending on the monthly heat-balance ratio γ.

$$E_p = \sum_{m=1}^{12} \frac{Q_{net,m}}{\eta_{sys,m}\eta_{gen,m}f_p} \tag{3}$$

4.2 Building description

A generic reference office building with cellular office spaces is assembled for this research, based on statistical data (BBRI, 2001). The reference building is a detached office building with 4 floors of 500 m^2 each, the floor plan of which can be found in Figure 2. The main axis of the building lies in east-west direction (the office zones façades facing south and north). The floor-to-floor height is 3.5 m, hence the building's total height is 14 m. This results in a protected volume of 7000 m^3, 2680 m^2 loss surface and a compactness of 2.6 m. The internal walls bounding the offices and the conference room are lightweight gypsum board walls. All other internal walls are heavy brick walls.

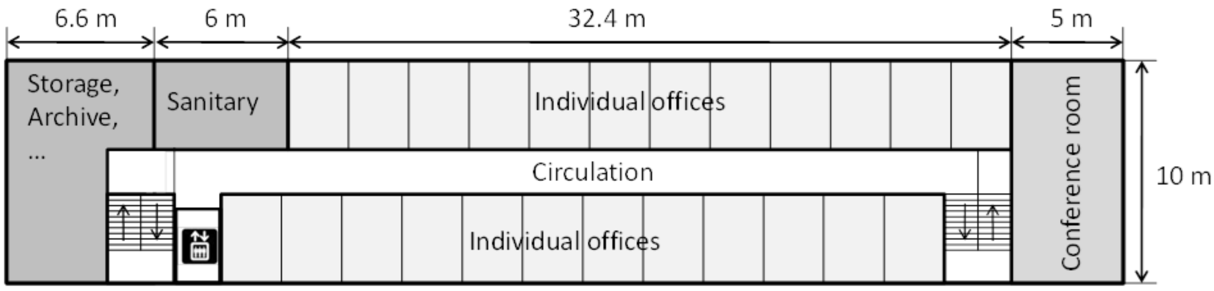


Figure 2: Floor plan of the medium-sized office building model.

As explained in section 4.1, the HVAC system is coupled to the different building design variants, in order to assess the influence of the interaction of the building and the system. A selection of 6 variants of the reference building is made. Table 2 offers a concise overview of the combinations of the building variables' values that form the building design variants. The imposed internal boundary conditions are described in Table 3. A typical weather data set for Uccle (Belgium) is used. The selection of building design variants is made to represent a wide range in annual net heating demand (NHD) (Table 4), while still allowing for passive cooling (Parys et al., 2012).

Table 2: Selected building design variants.

Nr.	**U_{wall}**	**U_{roof}**	**$U_{glazing}$**	**g-value glazing**	**Glass to wall ratio**	**Shading device**	**n_{50}**
	[W/m²K]	[W/m²K]	[W/m²K]	[-]	[%]		[ACH]
1	0.20	0.20	0.6	0.48	71	yes	1
2	0.40	0.30	1.1	0.59	21	no	2.5
3	0.20	0.20	1.1	0.26	31	no	1
4	0.40	0.30	1.1	0.44	21	yes	2.5
5	0.40	0.30	1.1	0.26	71	yes	2.5
6	0.60	0.40	1.1	0.29	31	yes	2.5

Table 3: Internal boundary conditions.

	Offices	**Meeting**	**Sanitary**	**Storage**	**Circulation**
Installed lighting power(1)	11 W/m^2	11 W/m^2	4.5 W/m^2	3.5 W/m^2	3.5 W/m^2
Occupancy (2)	9 am-6 pm (70% of nominal)	3rd floor: 10 am - 11 am and 2 pm - 3.30 pm (15 persons) 4th floor: 9 am - 10.30 am (15 persons)	8 am-6 pm	-	8 am-6 pm
Ventilation rate (3)	36 m^3/hpers supply	36 m^3/hpers supply (3.6 m^3/hm^2 non-occupied)	15 m^3/hm^2 extraction	3 m^3/hm^2 extraction	extraction
Int. gains (4) occupied	8.7 W/m^2	15 W/m^2	-	-	8 W/m^2
Int. gains (4) unoccupied	2 W/m^2	-	-	-	1 W/m^2
Heating set points (5)	21.5°C	21.5°C	16°C	16°C	-

(1) The lights are assumed to be switched on whenever the zone is occupied. The internal heat gains are 50% convective and 50% radiative.

(2) The sensible heat gain of 1 person is 75 W, 60% of which is convective. The latent heat gain of 1 person is 55 W or 0.081 kg/h (ASHRAE, 2009).

(3) Ventilation starts at 7 am and ends at 6 pm. 95% of the supplied fresh air is assumed to be extracted.

(4) Internal gains due to appliances based on ref. (Wilkins & Hosni, 2000). The split between convective and radiative gains is 50/50.

(5) Set point for operative temperature during occupancy. These are optimal operative temperatures for a metabolic rate of 1.2 met clothing values of 1 and 0.5 respectively, according to ISO7730 (ISO, 2005).

Table 4: Annual net heating demand for the selected building design variants.

Nr.	**NHD [kWh/m^{2}a]**
1	14.8
2	22.6
3	20.1
4	26.5
5	33.7
6	37.0

4.3 HVAC system

The system consists of a traditional hydronic heating system with a modulating condensing gas boiler and radiators in every heated zone (offices, meeting rooms, sanitary, storage, see section 3.2). No active cooling is provided. The heating system (Figure 3) is switched between 7 am and 6 pm during the heating season, i.e. from October 1st to June 1st. When there is no heating demand in the building, the boiler and the boiler circulation pump are switched off. The control of the system can be considered as good practice: thermostatic radiator valves (TRVs), supply temperature varying between 60°C and 45°C depending on the outside temperature (average of the previous 6 hours), variable speed pumps in distribution circuits with variable flow rate. The open header in the boiler circuit ensures a constant water flow rate. Since this is achieved by mixing return water from the secondary system with boiler outlet water, this will result in a higher inlet water temperature for the boiler and a reduced condensing effect.

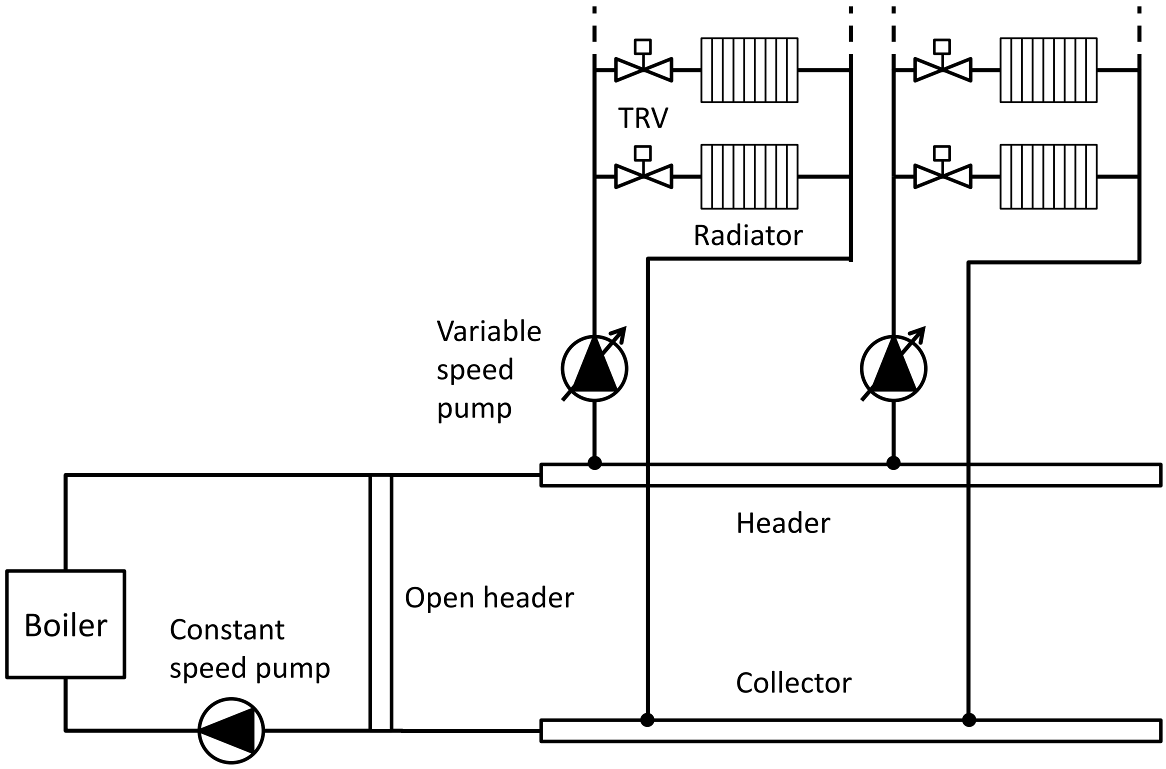


Figure 3: Schematic overview of radiator heating system (HVAC system 1) [1] .

The boiler is assumed to be located in an unheated basement, as is the horizontal main piping circuit, from which vertical piping leaves to supply the radiators. The vertical pipes thus run through the heated zones. Two parallel circuits are implemented, one for the south zone (offices and meeting rooms) and one for the north zone (offices, storage and sanitary).

Hygienic ventilation is provided with an extraction system consisting of window grilles for supply and constant speed fans for the extraction in the offices, the meeting room and the sanitary. This does imply however that the relative humidity in the zones cannot be controlled.

Since no active cooling is provided, this HVAC system typology cannot be applied in every office building design (see 4.2).

4.4 Integrated simulation model

The integrated building and systems model is set up in TRNSYS17 (Klein et al., 2010), a dynamic simulation tool well suited for HVAC system studies (Crawley et al., 2008). The time step is set at 1.5 minutes for these integrated models.

Only the 3rd and 4th floor of the building are modelled in the simulations, implying their energy demands to be representative for the entire building. This simplification can be justified by the good thermal insulation values of both roof and floor, while it drastically reduces the

[1] The system scheme shown is simplified to show only those components that influence the thermal calculations and are integrated in the simulation models. Indispensable hydraulic components such as balancing valves are not printed.

computational time. A multi-zone model with 14 thermal zones is defined: the 1-person offices are thus modelled as one single zone per floor and orientation (Figure 2).

The HVAC system component models and their main characteristics are summarized in Table 5. The selected and implemented component models are all able to describe part load performance and the influence of non-rated conditions. Transient effects are included as much as possible, as the thermal inertia of the heaviest elements (boiler, radiator) and most of the water or air content of the system (pipes, ducts, boiler, radiator) are modelled. The system thermal losses both during and in between periods of operation are thus mostly accounted for in the simulations.

Each thermal zone is represented by a single node in the TRNSYS building model (TRANSSOLAR, 2011). Hence, except for the control aspect, the emission efficiency cannot be calculated in this simulation set-up due to inherent limitations and is therefore a constant input. The generation and distribution efficiencies are calculated, though neglecting start-up phenomena for the former and valve inertia and inaccuracy for the latter.

No hydraulic calculations are included in the simulations, implying a perfectly balanced system is assumed. As a consequence, the auxiliary energy use for pumps and fans can only be calculated indirectly. For the pumps, this is done based on the model of (Bernier & Lemire, 1999), with which non-dimensional power curves as a function of non-dimensional volumetric flow rates are derived. The fan energy use is calculated as a function of the volumetric flow rate, using the polynomials proposed in AIVC technical note 65 (Schild & Mysen, 2009).

Table 5: Overview of the main HVAC system component simulation models.

Component	Model	Performance under non-rated conditions?	Part Load performance ?	Device thermal inertia?	Fluid content thermal inertia?
Gas boiler	(Haller et al., 2009)	Yes	Yes	Yes	Yes
Radiator	(Holst, 1996)	Yes	Yes	Yes	Yes
Pipes/ducts	Plug-flow	Yes	N.A.	No	Yes

5. RESULTS

Firstly, the integrated simulation is assessed in terms of simulation quality (5.1) and in terms of system sizing and implementation by evaluating the obtained thermal comfort (5.2). In section 5.3, the performance of the HVAC system is analyzed, focusing on monthly subsystem efficiencies, expressed depending on the heat-balance ratio and primary energy use. Subsequently, the results of this integrated approach are used to derive refined monthly subsystem efficiencies which are assessed and compared with the standard values of the subsystem efficiencies of the Flemish EPR calculation method in section 5.4.

5.1 Integrated simulation quality

The integrated model is computation-heavy, given the multitude of modelled components, the large differences in their time constants and the small calculation time step. A straightforward indicator to assess the convergence and correct execution of the simulation is to compare the difference in input and output of energy flows in the thermal system with the calculated energy losses. When this is calculated on a monthly basis, the error - denoted here as ΔQ_{sim} - thus found should be close to 0, though not necessarily equal to 0, as slight differences in internal energy between the beginning and end state are possible. The monthly simulation error, defined as the relative difference between the system energy input (heat produced by the boiler, $Q_{boiler,out}$) and output (heat emitted in the building zones, Q_{emit}), and the system's thermal losses (Q_{loss}).

$$\Delta Q_{sim} = \frac{(Q_{boiler,out} - Q_{emit}) - \sum Q_{loss}}{(Q_{boiler,out} - Q_{emit})} \tag{4}$$

The monthly simulation error is found to be on average 3.5%, with a maximum of 12.5%. This is deemed acceptable.

5.2 HVAC system performance

In all cases, the desired room temperatures are met, indicating that all systems components are properly sized for every respective building design variant and the control works well. Figure 4 illustrates this for building design variant 3 (Table 2) by showing the operative temperature in the north facing office zone on a random winter day.

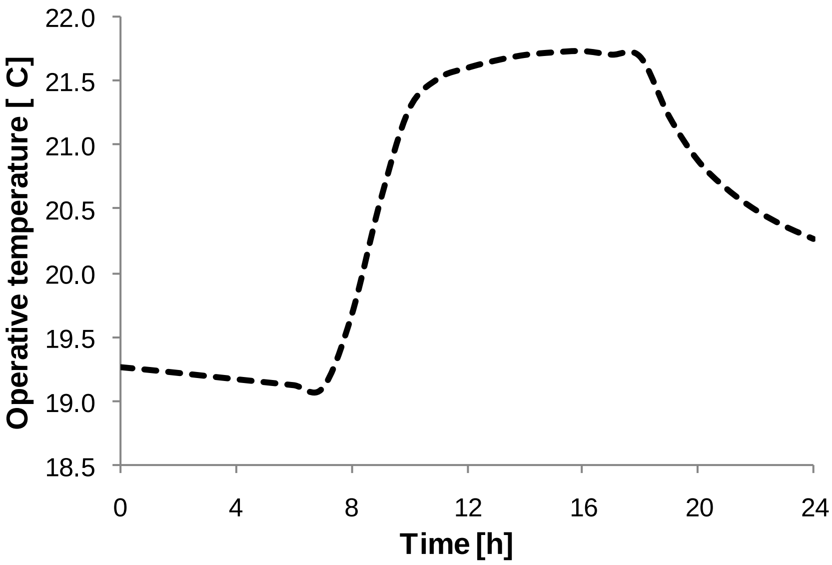
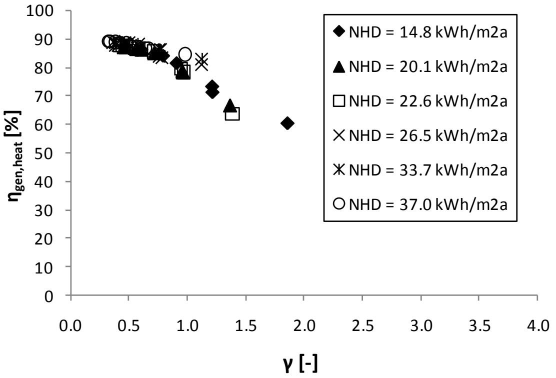


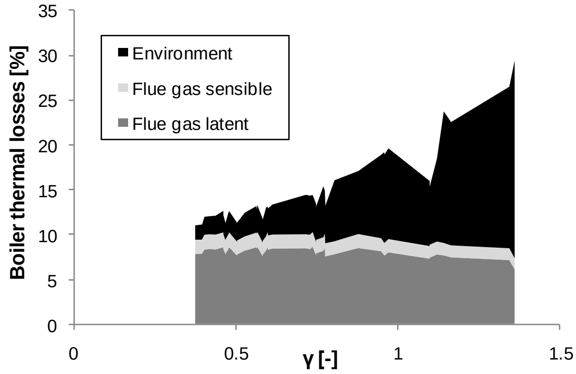
Figure 4: The daily operative temperature profile in north-facing offices between HVAC systems on a random winter day.

5.3 HVAC system performance analysis

5.3.1 Primary system efficiency

Figure 5a shows the monthly heat generation efficiency of the gas boiler as a function of the heat-balance ratio for the 6 selected building design variants. The efficiency drops significantly during months with higher heat-balance ratios - and thus lower part load ratios. When looking in detail to the boiler thermal losses proportional to the total heat production (Figure 5b), a decrease in latent flue gas losses is found for higher heat-balance ratios, due to the external temperature dependent heating curve resulting in lower water return temperature and thus more condensation. This small efficiency enhancement is however countered by a much greater increase in thermal losses to the surroundings. Lower part load ratios lead to intermittent boiler use and higher relative environment losses through cooling down between operational periods.



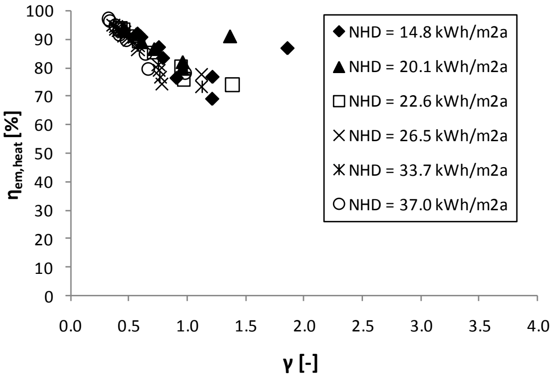


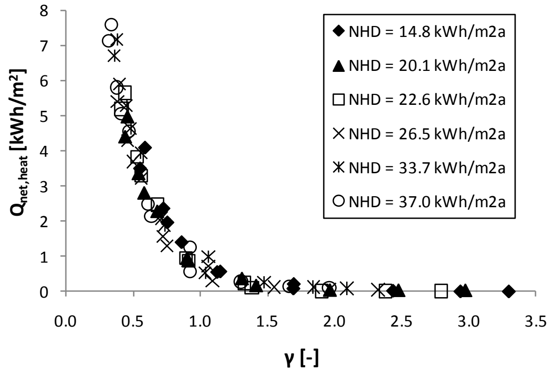
a) b)

Figure 5: a) Monthly heat generation efficiency; b) Boiler thermal losses.

5.3.2 Secondary system efficiency

Figure 6a shows the emission efficiency, calculated as the ratio of the net heating demand over the net energy delivered to the radiators. The emission efficiency consists of a factor including losses on component level, which is fixed at 95% (3.4), and a factor accounting for the control efficiency, shown in Figure 6a. The latter is thus about 1 at heat-balance ratios below 0.5, indicating the heat demand is met, but drops significantly for higher heat-balance ratios. This is due to overheating at times with very low heat demands due to imperfect control. A few outliers are found on the curve, but these represent months with negligible net heat demands (Figure 6b).





a) b)

Figure 6: a) Monthly heat emission control efficiency; b) Monthly net heat demand.

The distribution efficiency, defined as the ratio of the energy delivered to the radiators over the gross energy demand, is shown in Figure 7. A clear decreasing trend towards higher monthly heat-balance ratios is visible. This is due to the cooling down of the water in the system pipes in between heating periods gaining importance when the part load ratio drops.

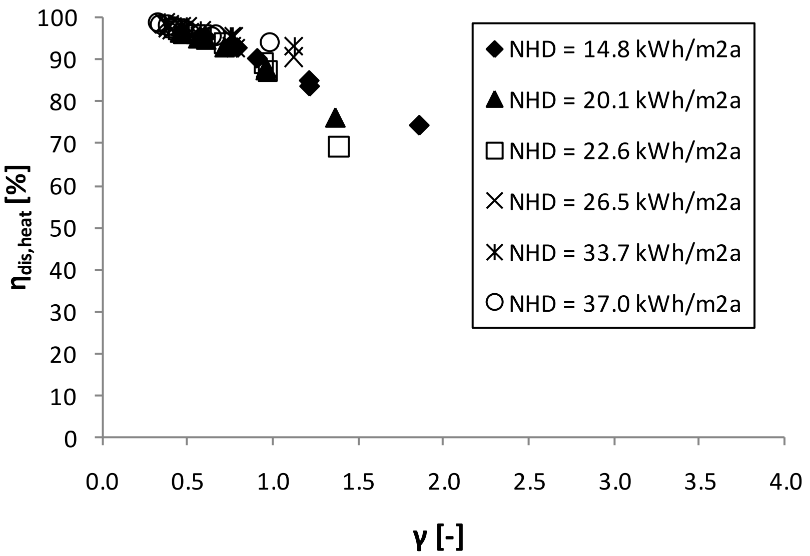


Figure 7: Monthly heat distribution efficiency.

5.3.3 Primary energy use

Table 6 summarizes the results of all integrated simulations in terms of total annual primary energy use of the HVAC systems in the selected building variants of Table 2.

The auxiliary energy use comprises the pumps, the fans and the boiler electrical energy use. The latter is negligible with values between 6 kWh and 10 kWh per month. The fan electrical energy use equals about 2200 kWh or 1.1 kWh/m2 per year. The pump energy use depends on the heat demand. When looking at the total primary energy use per building for heating and ventilating (Figure 8), the boiler gas consumption is by far the largest fraction, while the pump energy use constitutes only between 1% and 2%. Figure 8 clearly indicates the relatively increasing share of the auxiliary energy use for buildings with lower net heat demands in the total primary energy use, which will function as a mitigating secondary effect on potential energy savings.

Table 6: Total annual primary energy use of the HVAC system for the selected building design variants.

Nr.	**Total annual primary energy use [kWh/m^2]**
2	21.2
3	30.9
4	27.5
5	35.9
6	43.2
7	47.8

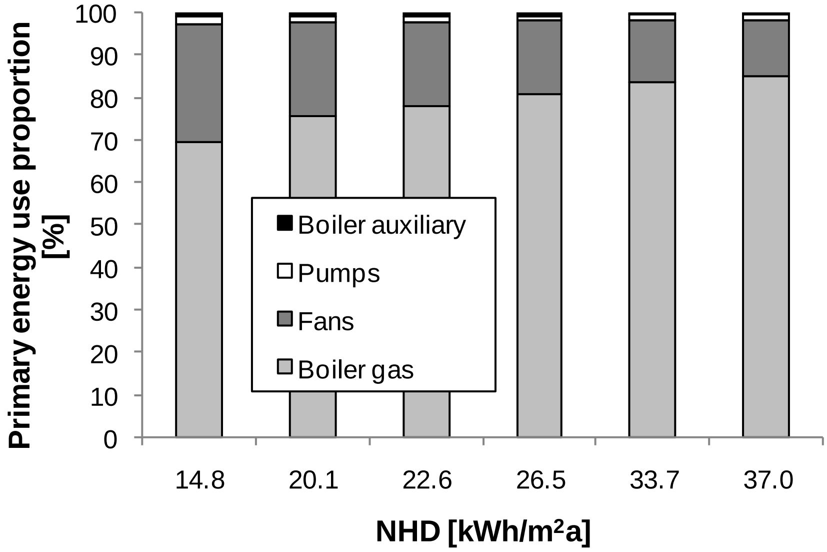


Figure 8: Breakdown of annual total primary energy use.

5.4 Calculation with refined monthly subsystem efficiencies

In a first section (5.4.1), correlations of the subsystem efficiencies as a function of the monthly heat-balance ratio are deduced based on the results of the integrated simulations. In the following section (5.4.2) the refined subsystem efficiencies are implemented in the EPR to evaluate their impact.

5.4.1 Subsystem efficiency regression models

Based on Figure 5 to Figure 7, correlations can be fitted expressing the monthly subsystem efficiencies depending on the heat-balance ratio γ_m, which can then be used in energy calculations of other buildings with similar thermal systems. The correlations are established as follows:

$$\eta_m = a\,\gamma_m^2 + b\gamma_m + c \tag{5}$$

Table 7: Regression coefficients and R2-values for the subsystem efficiency correlations

subsystem	**a**	**b**	**c**	**R^2**
Emission	0	-25.728	103.440	0.84
Distribution	-4.509	-9.417	102.690	0.84
Generation	-8.183	-3.888	91.688	0.90

5.4.2 Impact of EPR calculation with refined subsystem efficiencies

In this section, the impact of using the refined subsystem efficiencies depending on the monthly heat-balance ratio, as defined in Table 7, in EPR calculations of the monthly energy use is assessed by comparing the results with the default fixed values for subsystem efficiencies as defined in the Flemish EPR calculation software (see 3.1). In addition, the calculation with the refined subsystem efficiencies is compared to a calculation using annual average efficiencies deduced from the integrated simulations, to assess the influence of the dependency on the monthly heat-balance ratio.

The default value Flemish EPR value for a condensing gas boiler, based on the manufacturer's data for 30% part load ratio and corrected for the design return water temperature, equals 89.4%. This is quite comparable to the annual average efficiency of 87.1% that is found in the integrated simulations across all building variants. A default value of the system efficiency for hydronic secondary heating systems in buildings without a cooling system as defined in the Flemish EPR equals 85.5%. From the integrated simulations, average annual values of 96.4% for the distribution efficiency and of 91.2% for the emission efficiency are found. Combined, this yields a system efficiency of 87.9%, which is again close to the default EPR value. It can thus already be concluded that the EPR values are well chosen.

In Figure 9, the mean bias error (MBE) over the building variants, defined here for absolute values of the error, is shown for the 3 aforementioned EPR-type calculation methods for the monthly final energy use - dividing the monthly net heat demand by the monthly subsystem efficiency values - compared to the final energy use as calculated in the integrated simulations, which is thus regarded as the reference.

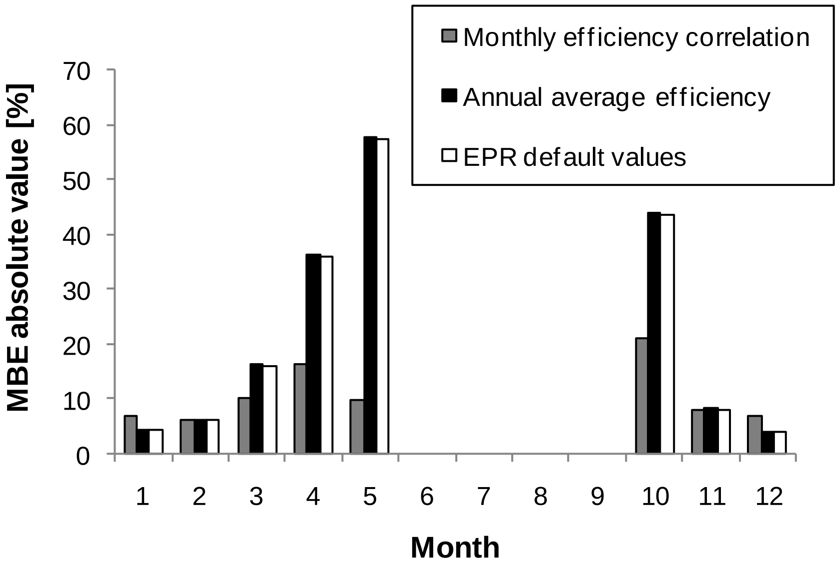


Figure 9: Comparison of the MBE (for absolute values of the error) of the 3 EPR type calculation methods for the monthly final energy use compared to the results of the integrated simulations.

As can be seen in Figure 9, the MBE is small and comparable for all 3 calculation methods in the winter months, when the heating demand is high. However, when going to the intermediate seasons, with lower demands and higher heat-balance ratios, the calculation with the refined subsystem efficiencies yields remarkable better results in terms of MBE. Thus, taking into account the dependency of the heat-balance ratio, integrating the subsystem efficiencies drop in months with higher heat-balance ratios, is shown to significantly improve the calculation results in months with lower demands.

However, the impact on the calculated annual final energy use for heating is quite modest. Where the calculation with the default EPR values yields a MBE of 7.2% compared to the results of the integrated simulation and the calculation with average annual efficiencies a MBE of 5.0%, the calculation with the refined subsystem efficiencies depending on the monthly heat-balance ratio yields an MBE of 3.9%.

6. DISCUSSION AND CONCLUSION

In this paper, integrated dynamic simulations of a thermal system coupled to 6 variants of a medium-sized office building are performed and discussed. A traditional hydronic heating system is considered, consisting of a modulating condensing gas boiler and radiators in every heated zone. No active cooling is provided, though only building variants able to provide summer comfort through passive cooling only are selected. Hygienic ventilation is provided by a mechanical extraction system.

From the integrated simulations, monthly efficiencies for the generation, distribution and emission subsystems are deduced. The latter are expressed depending on the monthly heat-balance ratio, which equals the ratio of heat gains over heat losses on the building level. The heat-balance ratio thus represents the part load ratio, but can be calculated without taking the system into account. This variable is used in order to generalize the results and at the same time use them in an EPR context, which requires relatively simple calculations where the system cannot be taken into account in detail.

The integrated simulations contain some model necessary model simplifications. The thermal inertia and water content of the most important is modelled, though not of all components. Moreover, the heat emission in the building zones is not modelled, as the latter are represented by a single thermal node. Finally, no hydraulic calculations are included, implying the assumption of a perfectly balanced system.

The resulting subsystem curves correlate quite well with the monthly heat-balance ratio (R^2-values of 0.84 or higher). These curves show the heating subsystem efficiency drops in months with higher heat-balance ratios (and thus lower heating demands). These refined efficiencies are subsequently used in an EPR-type calculation, in which the monthly net heating demand is divided by the subsystem efficiencies to estimate the monthly final energy use. The results of this calculation are compared to similar calculations using annually averaged efficiencies deduced from the integrated simulations and using the default fixed EPR values for the subsystem efficiencies. It is shown that using the refined efficiencies yields better results in intermediate months, when the heating demand is lower. However, when looking at the total annual final energy use, the impact of using the refined efficiencies is modest.

The subsystem efficiency curves depending on the monthly heat-balance ratio deduced in this paper are only valid for similar heating systems. In future work however, these curves will also be established for a selection of thermal systems (including active cooling) common in Belgium.

ACKNOWLEDGEMENTS

This research was funded by the Institute for the Promotion of Innovation through Science and Technology in Flanders (IWT-Vlaanderen). This support is gratefully acknowledged.

In addition, we would like to express our gratitude to dr. Stéphane Bertagnolio for his help in implementing thermal system component models.

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